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A High Statistics Measurement of the B_s^0 Lifetime

The DØ Collaboration
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We report a preliminary measurement of the B_s^0 lifetime in the semileptonic decay channel $B_s^0 \to D_s^- \mu^+ \nu X$, using approximately 400 pb^{-1} of data collected by the DØ detector during 2002-2004. We have reconstructed 5153 $D_s^- \mu^+$ candidates, from which we have measured the B_s^0 lifetime to be

$$\tau(B_s^0) = 1.420 \pm 0.043 \text{ (stat)} \pm 0.057 \text{ (syst) ps},$$

currently the most precise B_s^0 lifetime measurement.

Preliminary Results for Winter 2005 Conferences

I. INTRODUCTION

It is well known that in the Standard Model (SM), the B_s^0 mesons exist in two eigenstates of CP: $|B_s^{even}\rangle = \frac{1}{\sqrt{2}}(|B_s^0\rangle - |\bar{B}_s^0\rangle)$, and $|B_s^{odd}\rangle = \frac{1}{\sqrt{2}}(|B_s^0\rangle + |\bar{B}_s^0\rangle)$ with $CP\ |B_s^0\rangle = -|\bar{B}_s^0\rangle$. The mass eigenstates at time $t = 0$, B_s^H and B_s^L, (where H means "heavy" and L means "light") are linear combinations of $|B_s^0\rangle$ and $|\bar{B}_s^0\rangle$ too, e.g.:

$$|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle, \qquad |B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle, \tag{1}$$

with $p^2 + q^2 = 1$. In the SM, these mass eigenstates are approximately the CP eigenstates.

The mass and lifetime differences of the two mass eigenstates are defined by

$$\Delta m = m_H - m_L, \qquad \Delta\Gamma = \Gamma_L - \Gamma_H, \qquad \Gamma = \frac{\Gamma_H + \Gamma_L}{2}, \tag{2}$$

where $m_{H,L}$ and $\Gamma_{H,L}$ are the mass and decay width of B_s^H and B_s^L. Width difference in B_s^0 system is expected to be large in comparison with B^0 system, where is almost null. It is also expected that B_s^0 mesons are produced in an equal mixture of B_s^H and B_s^L, and its decay length distribution is described by a function [1] like

$$F(t) = e^{-\Gamma_H t} + e^{-\Gamma_L t} \qquad \text{with} \qquad \Gamma_{L,H} = \Gamma \pm \Delta\Gamma/2, \tag{3}$$

instead of just one exponential lifetime $e^{-\Gamma t}$, which is the functional form used in the measurement of the B_s^0 lifetime assuming a single lifetime.

It can be shown that the mean B_s^0 lifetime, $\tau(B_s^0)$, obtained from a fit assuming the single lifetime, is related with the total decay width, Γ, and the width difference $\Delta\Gamma$ by the relation

$$\tau(B_s^0) = \frac{1}{\Gamma}\frac{1 + (\Delta\Gamma/2\Gamma)^2}{1 - (\Delta\Gamma/2\Gamma)^2}. \tag{4}$$

In this note, we report a high statistics measurement of the B_s^0 lifetime, using the semileptonic decay $B_s^0 \to D_s^- \mu^+ \nu X$ [10], where the D_s^- meson was identified using its decay channel $D_s^- \to \phi\pi^-$, follow by $\phi \to K^+K^-$.

The data sample used in these studies consists of approximately 400 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected by the DØ detector at Fermilab during 2002-2004.

II. DATA RECONSTRUCTION

Events containing semileptonic B_s^0 decays are identified using a tight selection criteria for the muon present. We do not use any specific requirement at trigger level. We use muon candidates with $p_T > 2$ GeV/c and $p > 3$ GeV/c. This cut, as well as other higher p_T cuts in the selection, is used to reduce combinatorial background. In other analyses it can be lower but to improve signal significance one has to use impact–parameter or lifetime cuts. Those cuts are not used in this analysis in order to reduce any possible bias of the measurement.

The primary vertex is reconstructed on an event–by–event basis using a beam–spot constraint. The mean beam-spot position is determined on a run-by-run basis.

To reconstruct $D_s^- \to \phi\pi^-$, any pair of oppositely charged tracks with $p_T > 1.0$ GeV/c are assigned the kaon mass and combined to form a ϕ candidate. Each ϕ candidate is required to have a mass in the range 1.01-1.03 GeV/c^2 compatible with the reconstructed ϕ mass at DØ. The ϕ candidate is then combined with another track of $p_T > 0.7$ GeV/c. For the "right-sign" combinations we require that the charge of this track be opposite to the charge of the muon. This third track is assigned the pion mass. To have a good vertex determination, all selected tracks must have at least one SMT hit and one CFT hit. All tracks were clustered into jets using the DURHAM clustering algorithm with a p_T cut–off of 15 GeV/c [2, 3]. We require all particles to be in the same jet as the muon. In addition, all of the tracks are associated with the same primary vertex.

The three selected tracks must form a common D_s^- vertex. The confidence level of the combined vertex fit is required to be greater that 0.1%, and the p_T of the D_s^- candidate is required to be > 3 GeV/c.

The secondary vertex, where the B_s^0 decays to a muon and a D_s^-, is obtained by simultaneously intersecting the trajectory of the muon track with the flight path of the D_s^- candidate. The confidence level of that vertex should be

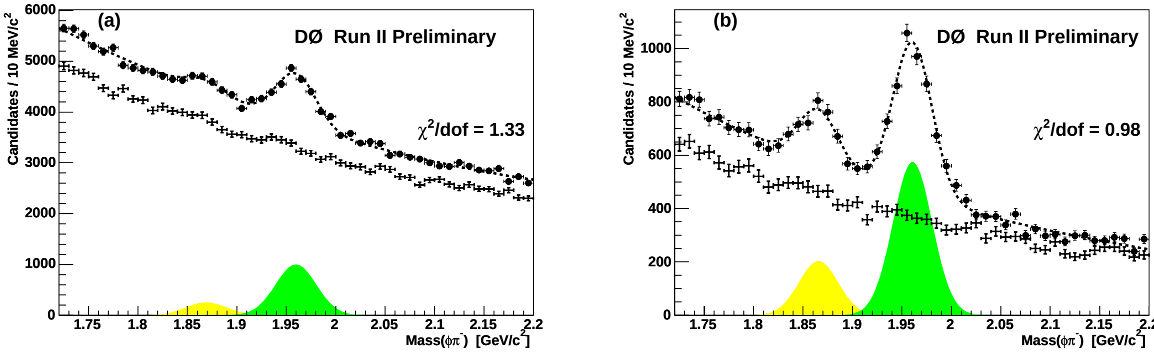

FIG. 1: (a) Mass distribution for D_s^- candidate events. Points with errors bars show the "right-sign" $D_s^-\mu^+$ combinations, and the crosses show the corresponding "wrong-sign" distributions. The dashed curve represents the result of the fit to the "right-sign" combinations. The mass distribution for the D_s^- signal is shown in green, and the D^- signal in yellow; (b) same distributions after requiring a significance of the pseudo-proper decay length greater than 5.

greater that 0.01%. To further reduce combinatorial background the reconstructed D_s^- decay vertex is required to be positively displaced from the primary vertex as projected along the direction of the D_s^- momentum.

Given the fact that ϕ has spin 1 and D_s^- and ϕ^- are spin 0 particles, the helicity angle (Φ), defined as the angle between the directions of the K^- and D_s^- in the ϕ rest frame, has a distribution proportional to $cos^2(\Phi)$. A cut of $|cos\Phi| > 0.4$ is applied to further remove combinatorial background, which was found to be flat. In order to suppress the physics background originated of $D^{(*)}D^{(*)}$ processes, we require that the transverse momentum of the muon with respect to the D, p_{Trel}, to be greater than 2 GeV/c. In the cases where we have more than one candidate per event, we choose the one with the best vertex probability $P_{\chi^2}(B_s)$. We also have required the pseudo–proper decay length (PPDL) uncertainty to be less than 500 microns (see Sec. III).

The resulting invariant mass distribution of the D_s^- candidates is shown in Fig. 1(a). Figure 1(b) shows the reconstructed invariant mass distribution of the D_s^- candidates after a cut on the significance of the PPDL greater than 5, i.e. $\lambda/\sigma(\lambda) > 5$. This cut is not applied for the rest of the analysis. D_s^- invariant mass distributions for "right-sign" $D_s^-\mu^+$ candidates are fit using a Gaussian to describe the signal and a second order polynomial to describe the combinatorial background. A second Gaussian is included for the Cabibbo-suppressed $D^- \to \phi\pi^-$ decay. The fit result is overlaid in the same figure. The width of the two signals has been forced to be equal. The fit yields a signal of 5153 ± 265 (stat) $\pm$ 450 (sys) events in the D_s^- peak and a mass of 1959.8 ± 1.0 MeV/c^2, slightly shifted from the PDG value of 1968.3 ± 0.5 MeV/c^2 [6]. The width of the Gaussian is 20.6 ± 1.0 MeV/c^2. The systematic uncertainty comes from the verification of the D_s^- signal yield, where we fixed the mean and width parameters to the one obtained from the tight cut sample, $\lambda/\sigma(\lambda) > 5$, and from the use of an exponential shape for the background. For the D^- the fit returns 1300 ± 223 events.

A. Monte Carlo

Some quantities in this analysis are determined using Monte Carlo methods. We have generated MC samples for that purpose using PYTHIA [3] for the production and hadronization phase, and EvtGen [4] for decaying the "b" hadrons produced. We generate B_s^0 meson samples with $c\tau = 439$ microns. Signal sample included the contributions from $D_s^-\mu^+\nu$, $D_s^{*-}\mu^+\nu$ $D_{s0}^{*-}\mu^+\nu$, and $D_{s1}^{'-}\mu^+\nu$. To save time D_s^- was forced to decay to $\phi\pi^-$ followed by $\phi \to K^-K^+$.

To be able to evaluate non-combinatorial backgrounds, we generated processes [11] like $\bar{B}^0 \to D_s^{(*)-}D^{(*)+}$, and $B^- \to D_s^{(*)-}D^{(*)0}X$, where the "right-sign" $D_s^-\mu^+$ combination can be obtained allowing $D^{(*)+/0}$ to decay semileptonically. The $B_s^0 \to D_s^{(*)-}D_s^{(*)+}X$ process was also generated.

To speed up the simulation of those samples, we applied some kinematic cuts at the generator level: muons had to have $p_T > 1.9$ GeV/c and $|\eta| < 2.1$, the kaons (and pions) from ϕ (D_s) had to have $p_T > 0.6$ GeV/c and $|\eta| < 3.0$, and the p_T of the D_s has to be > 1.0 GeV/c. The samples were then processed using the standard full simulation procedure.

B. Non–combinatorial Background

Apart from the background due to combinatorial processes like a real muon and a fake D_s^-, there could be real physics processes which will produce a real muon and a real D_s^-, where neither comes from the semileptonic decay of B_s^0. Those "right-sign" $D_s^-\mu^+$ combinations will be in the signal sample. Three sources of such events are identified: $B^0 \to D_s^{(*)+}D^{(*)-}X$, $B^+ \to D_s^{(*)+}D^{(*)0}X$, and $B_s^0 \to D_s^{(*)+}D_s^{(*)-}X$. In the first two processes, the $D^{(*)-}$ or the $D^{(*)0}$ decay semileptonically, while in the third contribution one of the two $D_s^{(*)}$ can decay semileptonically. These kind of events can be reconstructed as signal events, but the momentum of the lepton (muon) coming from the decay of the $D^{(*)}$ will be softer, since it comes from a secondary decay of a charm hadron. It is expected that such contributions will be small. To estimate the contribution of such processes to the signal, Monte Carlo events from these decays are used. The f_{D_sD} contributions are calculated as the ratio of the efficiencies and acceptances for the specific decays:

$$f_{D_sD} = \frac{\epsilon(b\bar{b} \to BX \to D_s^{(*)-}D^{(*)+}X')}{\epsilon(b\bar{b} \to B_s^0X \to D_s^{(*)-}\mu^+\nu X')}. \tag{5}$$

We found a contamination to the B_s^0 signal of 5.3% from $\bar{B}^0 \to D_s^{(*)-}D^{(*)+}X$ and $B^- \to D_s^{(*)-}D^{(*)0}X$ respectively and 4.6% from $B_s^0 \to D_s^{(*)+}D_s^{(*)-}X$. Uncertainties in branching ratios are used as sources of systematic uncertainty in the determination of the B_s^0 lifetime.

III. PSEUDO-PROPER DECAY LENGTH

The lifetime of the B_s^0, τ, is related with the decay length, L, by the relation

$$L = c\tau\beta\gamma = c\tau\frac{p}{m},$$

where $c\tau$ is the proper decay length, p is the total momentum, and m its mass. In the transverse plane this relation is transformed to

$$L_{xy} = c\tau\frac{p_T}{m},$$

where p_T is the transverse momentum of the B_s^0, and L_{xy} is the so-called transverse decay length. The decay length of the B_s^0 in the transverse plane is defined as the displacement of the B_s^0 vertex from the primary vertex projected onto the transverse momentum of the $D_s^-\mu^+$ system. If $\vec{X}$ is a vector which points from the primary vertex to the secondary vertex in the transverse plane, then we have

$$L_{xy} = \frac{\vec{X}\cdot \vec{p_T}(D_s^-\mu^+)}{|\vec{p_T}(D_s^-\mu^+)|}.$$

Now, when the B_s^0 decays semileptonically, it is not fully reconstructed and thus $p_T(B_s^0)$ is not determined with enough accuracy. The p_T of the $D_s^-\mu^+$ system is used as the best approximation. Then, a correction factor, K, has to be introduced. This K–factor is defined by

$$K = \frac{p_T(D_s^-\mu^+)}{p_T(B_s^0)}. \tag{6}$$

Therefore, the quantity used to extract the B_s^0 lifetime is called pseudo-proper decay length, denoted by λ, and defined by

$$\lambda = L_{xy}\frac{m(B_s^0)}{p_T(D_s^-\mu^+)} = c\tau\frac{1}{K}. \tag{7}$$

The correction factor K is determined using Monte Carlo methods. This correction is applied statistically by smearing the exponential decay distribution when extracting the $c\tau(B_s^0)$ from the PPDL in the lifetime fit. Figure 2(a) shows the obtained K–factor distribution for signal MC events, which has a mean value of 0.8656 and RMS 0.1031. The K distribution is approximately constant as a function of $p_T(D_s^-\mu^+)$ as shown in Fig. 2(b).

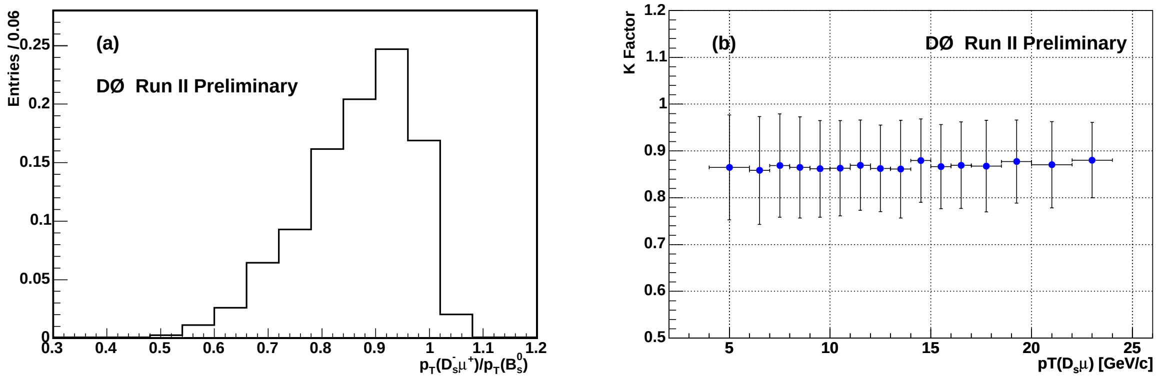

FIG. 2: Monte Carlo K–factor distribution for $B_s^0 \to D_s^- \mu^+ \nu X$. (a) Normalized K–factor distribution, (b) K–factor as a function of $p_T(D_s^- \mu^+)$.

IV. LIFETIME FIT

In order to perform the lifetime fit, we have defined a signal sample using the D_s^- mass distribution in the region from 1918.7 MeV/c^2 to 2000.9 MeV/c^2, corresponding to $\pm 2\sigma$ from fitted mean mass, 1959.8 MeV/c^2. The number of candidates in this region is 35955.

The PPDL distribution of the combinatorial background events, contained in the signal sample, was defined using "right-sign" events from the D_s^- sideband (2042.1-2124.3 MeV/c^2) and "wrong-sign" events from the interval 1795.4-2124.3 MeV/c^2.

We assume that the combinatorial background is originated by random track combinations, and then the sideband sample events can be used to model the background in the signal sample. This assumption is supported by the mass distribution of the "wrong-sign" combinations where no enhancement is visible in the D_s^- mass region (see Fig. 1). By adding the "wrong-sign" combinations to the "right-sign" sideband events, we better constraint the parameters of the combinatorial background events in the D_s^- signal sample.

The PPDL distribution obtained from the signal sample is fit using an unbinned maximum log-likelihood method. Both B_s^0 lifetime and background shape are determined in a simultaneous fit using the signal and background samples. The likelihood function $\mathcal{L}$ is given by the combinations of two parts

$$\mathcal{L} = \prod_i^{N_S} [f_{sig}\mathcal{F}^i_{sig} + (1 - f_{sig})\mathcal{F}^i_{bg}] \prod_j^{N_B} \mathcal{F}^j_{bg}, \tag{8}$$

where N_S is the number of events in the signal sample and N_B the number of events in the background sample. f_{sig} is the ratio of D_s^- signal events obtained from the D_s^- mass distributions to the total number of events in the signal sample.

A. Background Probability Function

The background probability distribution function (PDF), $\mathcal{F}^j_{bg}$, was defined for each measured PPDL λ_j as

$$\begin{aligned}
\mathcal{F}^j_{bg}(\lambda_j, \sigma(\lambda_j)) &= (1 - f_+ - f_{++} - f_-)G(\lambda_j, \sigma(\lambda_j)) \\
&+ f_+ \frac{e^{-\lambda_j/\lambda^+}}{\lambda^+} + f_{++}\frac{e^{-\lambda_j/\lambda^{++}}}{\lambda^{++}} \qquad (\lambda_j \geq 0) \\
&+ f_- \frac{e^{\lambda_j/\lambda^-}}{\lambda^-} \qquad (\lambda_j < 0),
\end{aligned} \tag{9}$$

where λ_j is the PPDL measurement for each data–point, $\sigma(\lambda_j)$ is the uncertainty in the determination of each PPDL, f_{++}, f_+, and f_- are the corresponding fractions of events in the exponential decays with positive–long, positive–short and negative–short PPDL, and λ^{++}, λ^{+} and λ^{-} are the corresponding slope of those exponential decays. G is the PDF for "zero" lifetime component. G is comprised of a narrow Gaussian resolution function and a very wide Gaussian distribution function to account for background from $c\bar{c}$ events:

$$G(\lambda_j, \sigma(\lambda_j)) = f_{s1} \cdot \mathcal{G}(\lambda_j, \sigma(\lambda_j), s_1) + (1 - f_{s1}) \cdot \mathcal{G}(\lambda_j, \sigma(\lambda_j), s_2), \tag{10}$$

where s_1 is the scale correction factor for the resolution and s_2 is the scale correction factor to account for $c\bar{c}$ events. f_{s1} is the actual fraction of events assigned to the resolution of PPDL.

B. Signal Probability Function

The signal probability distribution function $\mathcal{F}^{i}_{sig}$ is comprised by a normalized decay exponential function convoluted with a Gaussian resolution function and smeared with a normalized K–factor distribution function $\mathcal{H}(K)$. This function was defined as :

$$\mathcal{F}^{j}_{sig}(\lambda_j, \sigma(\lambda_j), s_1) = \int dK\ \mathcal{H}(K)\ \left[\frac{K}{c\tau(B^0_s)} e^{-K\lambda_j/c\tau(B^0_s)} \otimes \mathcal{G}(\lambda_j, \sigma(\lambda_j), s_1)\right], \tag{11}$$

where $c\tau(B^0_s)$ is the lifetime for B^0_s signal candidates and $\mathcal{G}$ is the resolution function.

Since a priori, we do not know the the overall scale of the decay length uncertainty, which we estimate on event-by-event basis, the scale factor, s_1, was introduced as a free parameter in the B^0_s lifetime fit.

The events originating from non-combinatorial background like the process $B \to D^{(*)-}_s D^{(*)}$ are also taken into account in the likelihood fit as terms like:

$$\int dK\ \mathcal{H}(K)\ \left[f_{D_sD} \frac{K}{c\tau(B)} e^{-K\lambda_j/c\tau(B)} \otimes \mathcal{G}(\lambda_j, \sigma(\lambda_j), s_1)\right], \tag{12}$$

where f_{D_sD} is the fraction of the $D^{(*)}_s D^{(*)}$ process found in the B^0_s signal sample as describe above. $c\tau(B)$ is the lifetime of the corresponding B meson, taken from the world average [6]. This lifetime is scaled by the ratio of masses, $\mathrm{M}(B^0_s)/\mathrm{M}(B)$, to account the fact that the mass of the B^0_s is used in the determination of the PPDL.

V. FIT RESULTS

Adding all pieces together, we performed the simultaneous fit to the signal and background samples, where we allowed the parameters for B^0_s lifetime ($c\tau(B^0_s)$), background description (λ_-, λ_+, λ_{++}, f_-, f_+, and f_{++}), and the scale factors parameters (s_1, s_2, and f_{s1}) to float. After performing MIGRAD-HESSE-MINOS [7] the fitted values and their statistical uncertainties are shown in Table I. The B^0_s lifetime was

$$\tau(B^0_s) = 1.420 \pm 0.043 \text{ ps.}$$

Figure 3 shows the pseudo-proper decay length distribution of the signal sample with the fit result superimposed (dashed curve). The dotted curve represents the sum of the background probability function over the events in the signal sample. The B^0_s signal is represented by the filled histogram.

VI. CONSISTENCY CHECKS AND SYSTEMATIC UNCERTAINTIES

We have performed several cross–checks of the lifetime measurements. In particular, Monte Carlo methods has been used to the look for biases in the fitting procedure; the mass windows, defining signal and background samples, has been varied; the reconstructed B^0_s mass has been used instead of the world average [6]; and the sample has been splitted into different kinematical regions. All results obtained with these variations are consistent with our central value.

Table II summarizes all of the studied systematic uncertainties, the current largest contribution comes from background estimate, where the left side band was used and a relatively large shift in lifetime was observed. Pending further detailed studies of background and verification with a high–statistics sample of $B^+ \to \mu^+ D^0 \nu X$, a systematic error of half of the observed lifetime shift, i.e., 15 μm, is conservatively assigned due to background uncertainties.

Parameter	Value	Statistical Uncertainty	Units
f_-	0.108	0.002	
f_+	0.222	0.004	
f_{++}	0.050	0.004	
λ^-	133	3	μm
λ^+	206	4	μm
λ^{++}	674	22	μm
s_1	1.568	0.007	
s_2	13.634	0.322	
f_{s1}	0.945	0.003	
$c\tau(B_s^0)$	426	13	μm

TABLE I: Result of the Simultaneous Fit to the B_s^0 Semileptonic Data Sample.

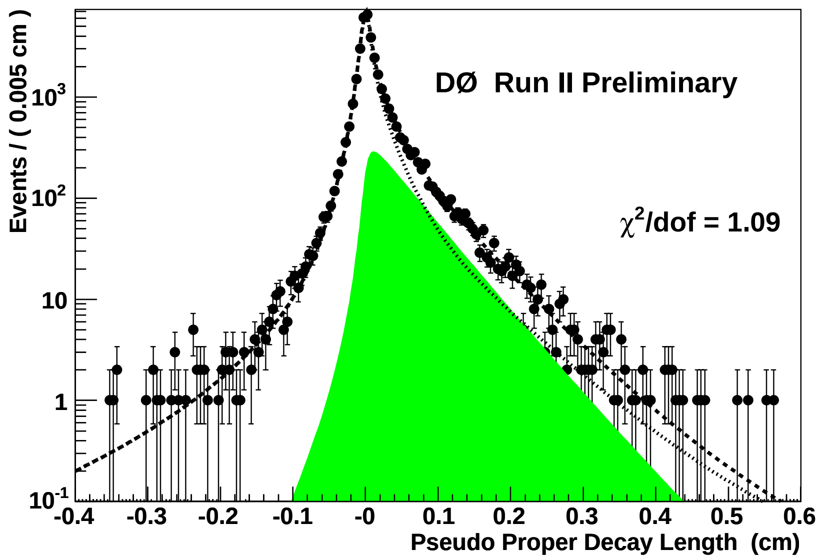

FIG. 3: Pseudo-proper decay length distribution for B_s^0 semileptonic data with the result of the fit superimposed. The dotted curve represents the combinatorial background and the filled histogram represents the B_s^0 signal.

VII. CONCLUSIONS

Using an integrated luminosity of approximately 400 pb^{-1}, we have measured the B_s^0 lifetime in the decay channel $D_s^- \mu^+ \nu X$ to be

$$\tau(B_s^0) = 1.420 \pm 0.043(\text{stat}) \pm 0.057 \text{ (syst) ps}, \tag{13}$$

Source	$\Delta c\tau$ (μm)
Detector alignment [8]	±5.0
Background estimate	±15.0
Selection criteria	$+3.6$
Decay length resolution	±1.6
K–factor determination	$^{+3.5}_{-4.1}$
Non-combinatorial background	$^{+3.6}_{-4.4}$
Total	$\pm$**17.0**

TABLE II: Summary of systematic uncertainties

Experiment	dataset	$\tau(B_s^0)$ (ps)
World Average(PDG) [6]		1.461 ± 0.057
ALEPH	91-95	$1.54^{+.14}_{-0.13} \pm 0.04$
CDF	92-96	$1.36 \pm 0.09^{+0.06}_{-0.05}$
DELPHI	91-95	$1.42^{+0.14}_{-0.13} \pm 0.03$
OPAL	90-95	$1.50^{+0.16}_{-0.15} \pm 0.04$
Average of $D_s l$ measurements [9]		1.442 ± 0.066
This Measurement	**02-04**	$\mathbf{1.420 \pm 0.071}$

TABLE III: Previous lifetime measurements.

where a single exponential description has been used. The result is in good agreement with the current world average values: $\tau(B_s)_{HFAG} = 1.442 \pm 0.066$ ps [9]. Table III shows the most recent semileptonic measurements. The present B_s^0 lifetime measurement is also consistent with the world average measurement $\tau(B_s)_{PDG} = 1.461 \pm 0.057$ ps [6], where semileptonic and hadronic decays were combined, and it is the current best measurement.

Acknowledgments

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[9] "Averages of b-hadron Properties as of Summer 2004", J. Alexander *et al.* (Heavy Flavor Averaging Group), hep–ex/0412073.
[10] Unless otherwise stated, references to a specific charge state imply the charge conjugate as well.
[11] $D^{(*)}\bar{D}^{(*)}$ will stands for the sum of $D^*\bar{D}^*$, $D^*\bar{D}$, $\bar{D}D^*$, and $D\bar{D}$. When $D^{(*)}$ appears alone, it will denote either D, D^* or D^{**}.